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Modelling Pollutant Washoff from South East Queensland Catchments Australia

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ABSTRACT
The progressive development and urbanisation of catchments alter catchment hydrology and affects stormwater runoff quality. Urban runoff carries pollutants into natural waterways and affects stream water quality. The rapid urban development in coastal areas of South East Queensland has made a significant impact on natural waterways in the region. Efforts to develop predictive models to estimate pollutant washoff, particularly in subtropical Australia, have been limited due to acute shortage of recorded water quality data.

This paper presents a study on pollutant washoff by analysing the hydrological and water quality data of three catchments in Gold Coast region in South East Queensland, Australia. The catchments are characterised by differing forms of land development and housing density ranging from predominantly forested, to rural acreage residential (un-sewered), to urban residential (sewered). The catchments have the same geological formations and similar soil types.

This paper examines the role of rainfall in pollutant washoff and explores the interactions of various pollutants in order to develop simple predictive equations to estimate pollutant loads from rainfall characteristics. It has been found that total phosphorus washoff in an urban catchment is greater than that of the nearby forested catchment and total phosphorus shows a strong correlation with total suspended solids in the storm runoff. Simple prediction equations are developed to predict total phosphorus from total suspended solids and the equations show satisfactory goodness-of-fit and satisfy the underlying model assumptions very well.

This is an ongoing research project and the results from this exploratory analysis will form the basis of in-depth understanding and developing models of pollutant buildup and washoff processes from subtropical catchments in Australia.

KEY WORDS: urban runoff quality, pollutant washoff, urban stormwater pollution, water quality, catchment urbanisation

INTRODUCTION
Increased urbanisation generally results in greater runoff volume, quicker catchment response and deteriorated runoff quality. The concentrations of various pollutants such as biochemical oxygen demand, suspended solids, phosphorus, nitrogen and heavy metals

are generally higher in urban runoff than that from the forested catchments. The processes of pollutant buildup and washoff from urban areas have been reviewed by Duncan (1995a, b, c). Drapper et al. (2000) examined the quality of road runoff from Brisbane. Stormwater management model SWMM is based on the assumption that pollutant loading is a linear function of time since the last rainfall. Chew et al. (1997) argued that pollutant load is relatively constant over the catchment and washoff is strongly related to rainfall intensity rather than being limited by buildup time.

There have been limited studies on pollution buildup and washoff in sub-tropical and tropical parts of Australia. The research outcomes from South East Australian catchments may not be strictly applicable to sub-tropical and tropical regions of Queensland because these areas have quite distinct hydro-geological characteristics (e.g. rainfall intensity and durations are relatively higher in Queensland than those of Victoria and New South Wales). A collaborative research project between Queensland University of Technology (QUT) and Gold Coast City Council (GCCC) has been undertaken to understand pollutant buildup and washoff process in Queensland catchments. Three small catchments have been selected for the research: one of these is fully urbanised, the second one is semi-urbanised and the remaining one is mostly forested. The particular focus of this paper is to investigate the role of rainfall in pollutant washoff, to explore the interactions of various pollutants and to develop simple prediction equations to estimate a particular pollutant from rainfall characteristics and/or other easily measurable pollutants. The results from this exploratory analysis will assist to identifying further research tasks for developing pollutant buildup and washoff process models for catchments in subtropical and tropical Australia.

STUDY CATCHMENTS

Three catchments in the Gold Coast region in South East Queensland, Australia were selected for the study: Upper Bonogin Valley, Bonogin Valley and Highland Park catchments. The Upper Bonogin Valley catchment is mostly forested, while the Bonogin Valley catchment is a combination of rural residential and forest and the Highland Park catchment is predominantly urban residential. The catchments are all based on same geological unit and have similar soil types. The locations of the catchments are shown in Figure 1 and the catchment characteristics are summarised in Table 1. The study catchments have been mapped in detail, including detailed landuse, geology, soils, topography and stream morphology (GCCC, 2001).

DATA COLLECTION

Water quality data is collected from a sampling point at the bottom of each of the three catchments. Automatic monitoring stations have been established in each catchment to record rainfall (mm), streamflow (L/s), pH, electric conductivity (EC), temperature and dissolved oxygen concentration (DO, mg/L). Automatic sampling devices are used to collect event samples to augment grab samples taken during low flow conditions. The physical samples are analysed for pH, EC, total organic carbon (TOC), mg/L, total suspended solids (TSS), mg/L, total nitrogen (TN), mg/L and total phosphorus (TP), mg/L.

The streamflow, rainfall and water quality data, collected from July/ 1999 to July/ 2001 (about 2 years), were used in this study. To examine the relationship of pollutant washoff with rainfall characteristics, the rainfall data were accumulated into hourly intervals and a rainfall event was defined as a period of 'significant' precipitation preceded and followed by at least 6 hours of no rainfall period. The detailed method of rainfall events selection can be found in Rahman et al., (2001). The duration of the rainfall event (D, hour), rainfall intensity (I, mm/h) and total rain (R) were thus obtained. A total of 20, 26 and 29 rainfall events and water quality data points were assembled for Upper Bonogin Valley, Bonogin Valley and Highland Park catchments, respectively.

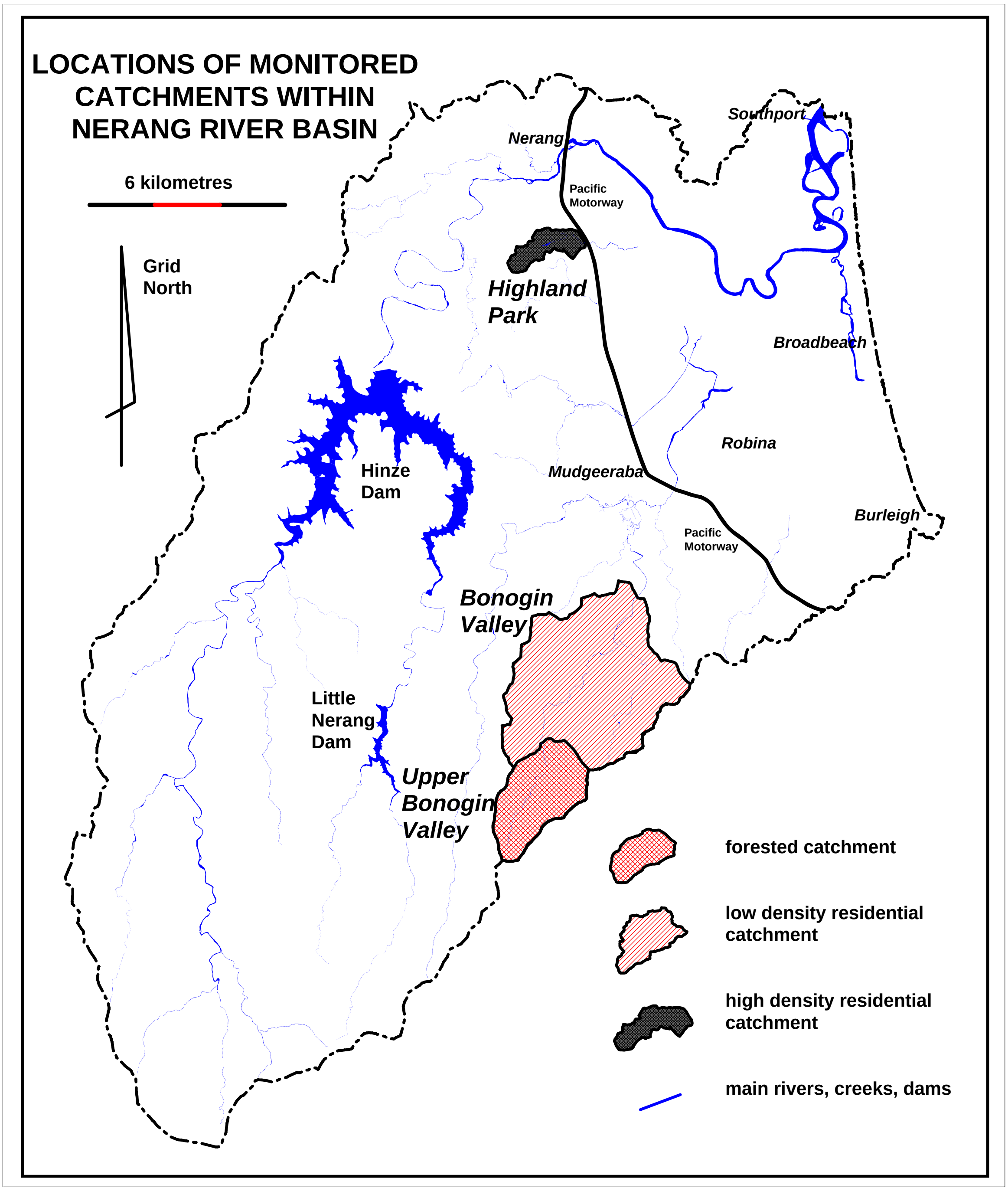

Figure 1 Map showing the study catchments

RESULTS

The correlation matrices of the rainfall characteristics and various pollutants for the three catchments are provided in Tables 2, 3 and 4, respectively. The correlation coefficients for total suspended solids (TSS) with rainfall intensity (I) at Upper Bonogin Valley, Bonogin Valley and Highland Park catchments are -0.30, 0.38 and -0.09, respectively. This implies that as the Upper Bonogin Valley catchment is mostly forested, the runoff is cleaner i.e. the concentration of TSS does not increase with rainfall intensity and due to dilution effects, TSS decreases with increased runoff volume. For the Bonogin Valley catchment, TSS increases with rainfall intensity indicating that sediment in the runoff increases with rainfall. This may be due to erosion from unpaved roads, driveways and the use of earthen road drains instead of kerb and channelling in the semi-urbanised catchment. For the Highland Park catchment, as the catchment is fully urbanised and mostly impervious, the runoff contains a relatively lower sediment load and TSS does not increase with rainfall intensity.

Table 1 Selected study catchments and their geology and soil characteristics

Catchment name	Area (ha)	Landuse	Geology	Soil (Isbell 1996)
Upper Bonogin Valley Catchment (Bonogin)	647	Forest land: 79% Rural residential: 19% Road reserve: 2%	Alluvium: 1.1% Binaburra Rhyolite: 3.5% Neranleigh-Fernvale beds: 95.4%	Grey Dermosols and Rudosols: 1.1% Brown Dermosols and Chromosols: 3.5% Red, Brown, Yellow and Grey Kurosols, Red Ferrosols and Tenosols: 95.4%
Bonogin Valley Catchment (Hardy)	2726	Forest land: 40.5% Rural residential: 54.9% Road reserve: 4.6%	Alluvium: 2.1% Binaburra Rhyolite: 0.8% Neranleigh-Fernvale beds: 97.1%	Grey Dermosols and Rudosols: 2.1% Brown Dermosols and Chromosols: 0.8% Red, Brown, Yellow and Grey Kurosols, Red Ferrosols and Tenosols: 97.1%
Highland Park Catchment (Hinkler)	161	Forest land: 9.2% Rural residential: 2.8% Urban residential: 60.4% Road reserve: 16.3% Other (commercial, grazing land etc): 11.3%	Neranleigh-Fernvale beds: 100%	Red, Brown, Yellow and Grey Kurosols, Red Ferrosols and Tenosols: 100%

The correlation coefficients for total phosphorus concentration (TP) with rainfall intensity (I) at Upper Bonogin Valley, Bonogin Valley and Highland Park catchments are -0.04, 0.25 and 0.21, respectively. At the Upper Bonogin Valley catchment, the concentration of TP does not increase with rainfall intensity indicating that there is little phosphorus built up in the catchment, which is as expected as the catchment is mainly forested. For the Bonogin Valley (semi-urbanised) and Highland Park (fully urbanised) catchments, the concentration of TP in the runoff increases with rainfall intensity, as shown in Figure 2. There are some data points in this figure for which TP levels do not increase with rainfall intensity. On further analysis, it was found that the associated storm losses are very high for these events with little runoff and thus the phosphorus levels in the samples do not show a high level.

Some of the pollutants show strong correlation with other pollutant parameters. Total phosphorus shows a strong correlation with total suspended solids (TSS) for Upper Bonogin Valley catchment (r = 0.89) and at the Highland Park catchment (r = 0.85), as shown in Figure 3. Also total nitrogen (TN) shows a reasonably high correlation with TSS for Upper Bonogin Valley catchment (r = 0.60) and at the Highland Park catchment (r = 0.56). These results indicate that in these two catchments TSS may be acting as a carrier for phosphorus and nitrogen. Also, total organic carbon shows a reasonably high correlations with TSS for both the Upper Bonogin Valley (r = 0.45) and Highland Park (r = 0.47) catchments. The high correlation for the Upper Bonogin Valley catchment would indicate that leaf litter may be forming a significant component of the TSS in the runoff as it is forested. Similarly the high correlation for the Highland Park catchment could be due to washoff from gardens such grass clippings etc. The low correlation between TSS and TOC (r = 0.06) for the Bonogin Valley catchment clearly indicates that the TSS is mostly inorganic in nature and is due to soil erosion as discussed previously.

Prediction equations were developed with a view to evaluating a pollutant parameter given the rainfall characteristics and/or other easily measurable pollutant characteristics. These equations can assist in reducing sampling and testing efforts for some of the pollutants and can be useful in detecting data errors. Also, these equations can be used to investigate the interactions between various pollutants, which may be useful to better understand the pollutant buildup and washoff processes in the study catchments. The statistical package SPSS was used to develop these equations.

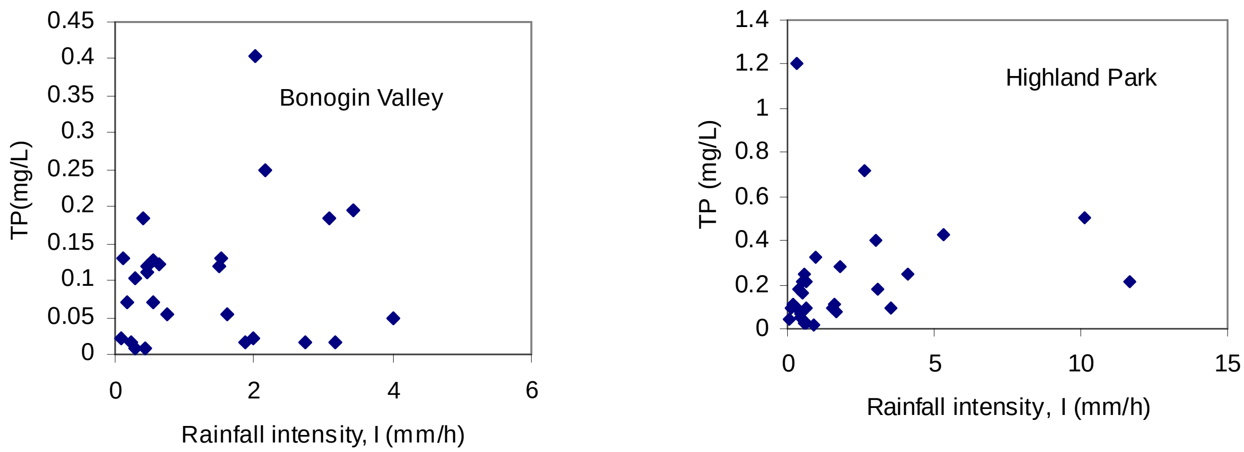

Figure 2 Relationship of total phosphorus (TP) with rainfall intensity (*I*) for Bonogin Valley and Highland Park catchments

Table 2 Correlation matrix for Upper Bonogin Valley catchment

	D	I	R	DO	TN	TP	pH	Flow	EC	TOC
I	-0.25									
R	0.51	0.42								
DO	0.04	0.25	0.11							
TN	0.01	-0.12	0.14	-0.07						
TP	-0.21	-0.04	-0.09	0.12	0.55					
pH	0.43	-0.05	-0.05	-0.11	0.01	0.08				
Flow	-0.15	0.15	0.22	-0.10	0.04	-0.02	-0.42			
EC	-0.14	-0.24	-0.14	0.15	0.09	-0.50	-0.08	0.04		
TOC	-0.07	-0.18	-0.14	0.13	0.17	0.52	0.01	-0.11	-0.28	
TSS	-0.09	-0.15	0.12	-0.14	**0.60**	**0.89**	-0.11	0.03	-0.37	**0.45**

Table 3 Correlation matrix for Bonogin Valley catchment

	D	I	R	DO	TN	TP	pH	Flow	EC	TOC
I	-0.22									
R	0.51	0.41								
DO	0.05	-0.08	0.08							
TN	0.02	0.06	0.10	-0.51						
TP	-0.09	**0.25**	0.39	0.44	-0.21					
pH	0.31	0.09	0.24	-0.12	0.15	-0.32				
Flow	-0.23	0.16	0.22	-0.01	0.05	**0.36**	-0.54			
EC	-0.14	0.09	-0.14	0.46	-0.41	-0.04	-0.36	0.09		
TOC	-0.06	-0.18	-0.16	-0.03	0.22	0.03	0.17	-0.18	-0.12	
TSS	-0.08	**0.38**	0.22	-0.10	**0.31**	**0.24**	0.13	0.05	-0.55	0.06

For Upper Bonogin Valley catchment, the following prediction equation was developed:

TP = 0.011 + 0.001 (TSS), N = 18, R^2 = 95%, SEE = 25% of mean TP (1)

Where TP is the total phosphorus in mg/L, TSS is the total solids in mg/L, N is the number of data points used to develop the prediction equation (excluding the outliers, if any), R^2 is the coefficient of determination, and SEE is the standard error of estimates as % of mean of the dependent variable.

For Highland Park catchment, the following prediction equations were developed:

TN = 1.104 + 0.016 (TSS), N = 26, R^2 = 70%, SEE = 76% of mean TN (2)

TP = 0.04 + 0.026 (I) + 0.001 (TSS), N = 29, R^2 = 82%, SEE = 49% of mean TP (3)

Where TN is the total nitrogen in mg/L, I is the rainfall intensity in mm/h and other variables are as mentioned above.

Table 4 Correlation matrix for Highland Park catchment

	D	I	R	DO	TN	TP	pH	Flow	EC	TOC
I	-0.24									
R	0.49	0.48								
DO	0.28	0.44	0.56							
TN	0.01	-0.09	-0.14	-0.53						
TP	-0.19	**0.21**	0.09	-0.19	**0.37**					
pH	0.19	-0.52	-0.16	-0.18	0.41	0.08				
Flow	-0.09	0.22	0.26	-0.16	-0.15	0.02	-0.93			
EC	-0.02	-0.26	-0.26	0.07	-0.14	-0.24	0.44	-0.44		
TOC	-0.15	-0.23	-0.29	0.19	**0.50**	**0.37**	0.15	-0.20	-0.03	
TSS	-0.05	**-0.09**	-0.16	-0.44	**0.56**	**0.85**	0.23	-0.01	-0.23	**0.47**

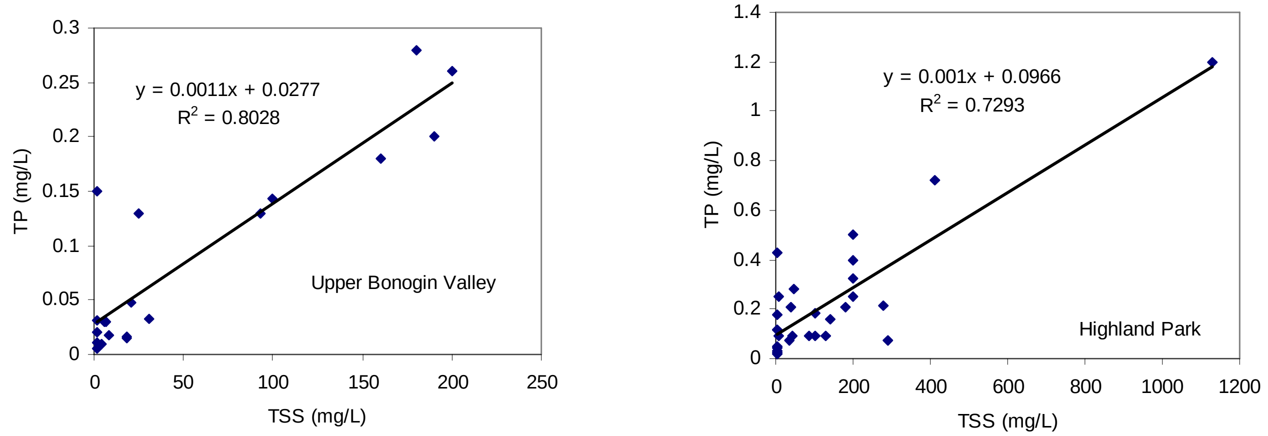

Figure 3 Relationship between total phosphorus (TP) and total suspended solids (TSS) at Bonogin and Hinkler catchments

The predictor variables were entered into the equations at a minimum significance level of 0.05. The outliers and influential data points were disregarded in developing the equations. The developed equations were tested to determine whether the underlying assumptions of regression analysis (least squares assumptions) are satisfied. Standardised residuals were plotted against the standardised predicted values, which did not show any pattern (Figure 4). The normal cumulative probability plots did not show much departure from straight line indicating that residuals were near normally distributed. Also, the predicted and observed values did not show any pattern. These results show that the developed prediction equations are statistically meaningful and confidence can be placed on them.

The values of coefficient of determination (R^2) for Equations 1 and 3 are 95% and 82% and standard error of estimates (SEE) are 25% and 49% of the observed mean value of total phosphorus (TP). These results indicate that TP can be predicted from total suspended solids (TSS) at the Upper Bonogin Valley catchment, and from TSS and rainfall intensity (I) at the Highland Park catchment with reasonable accuracy. Total nitrogen (TN) can be predicted from TSS at Highland Park catchment with reasonable accuracy (the R^2 of the equation is 70%). No meaningful prediction equations were identified for Bonogin Valley catchment at the present time. The difficulty in developing predictive equations may be attributed to the mix of land uses in this catchment which consists of about 59% rural residential and 41% forest. With a larger data set that will be available in the near future as a part of the on-going research, more meaningful prediction equations will be developed for all of the study catchments.

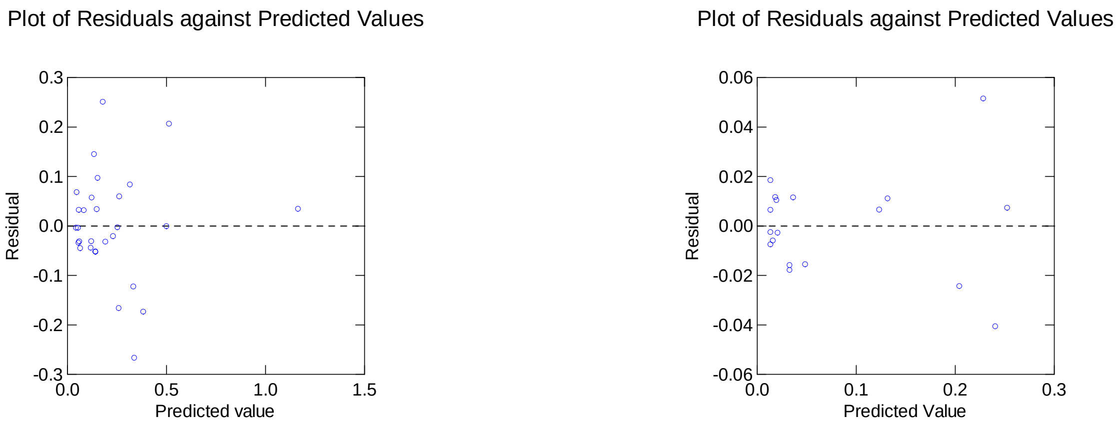

Figure 4 Plots of standardised residuals against standardised predicted values for the prediction equations for total phosphorus (Equations 1 and 3, respectively)

CONCLUSION

The stormwater runoff quality of three catchments in the Gold Coast region in South East Queensland Australia is examined. These catchments have differing forms of land development and housing density ranging from predominantly forested to rural acreage residential and to urban residential. Following conclusions can be drawn from this empirical study:

- For the forested catchment (Upper Bonogin Valley), total phosphorus concentration does not increase with rainfall intensity, but for the semi-urbanised (Bonogin Valley) and urban residential (Highland Park) catchments, total phosphorus concentration increases with increased rainfall intensity. This implies a higher phosphorus source on the semi-urbanised and urbanised catchments as compared to forested one.
- Total phosphorus shows a strong correlation with total suspended solids in both the forested and urban catchments, which indicate that total suspended solids is a carrier for phosphorus.
- Predictive equations were developed for the forested (Upper Bonogin Valley) and urban (Highland Park) catchments to predict total phosphorus from total suspended solids and from rainfall intensity and total suspended solids respectively. The equations show high coefficient of determination (95% and 82%) and small standard error of estimates (25% and 49%), and satisfy model assumptions very well.

With increased volume of data that will be available as a part of the ongoing research project, more meaningful prediction equations can be developed in future. These will require understanding of the physical significance of the developed models and a proper model validation technique. The results from this limited data analysis will be useful in developing strategy for future data monitoring, analyses and modelling in these catchments.

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